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Tropical tree carbon storage at Drago Dos Forest in Boca Del Drago, Panama

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ABSTRACT

Currently, anthropogenic carbon emissions pose a significant, global threat, contributing to Global Warming and Climate Change (CC). Today, the most effective carbon sinks are natural. Trees are highly effective carbon sinks that sequester large amounts of atmospheric carbon dioxide (CO_2), most greatly in tropical areas. However, tropical tree carbon storage needs to be more accurately estimated to provide valuable information toward mitigating CC and its negative environmental effects. This study aimed to estimate CO_2 sequestration at a tropical forest in Boca Del Drago, Panama, and compare it to that of a nearby mangrove forest. It was hypothesized that the tropical forest, named Drago Dos, would be found to store above average amounts of carbon, and that the mangrove forest would store carbon even more efficiently. To accomplish this, random plots within each forest were selected, totaling ~500 m^2 at each site. Within each plot, trees were measured for diameter at breast height (DBH) using diameter tape and tree height using a range finder. Then, the stored carbon for each tree was calculated, summed, and converted using allometric equations developed for the respective ecosystems. It was found that Drago Dos stored 557 tons/ha CO_2, higher than the regional average for a mature forest. The mangrove forest was estimated to store only 329 tons/ha CO_2. However, tropical carbon storage was not significantly higher per hectare than mangrove carbon storage ($p= 0.39$). These results indicate that Drago Dos Forest is a healthy, mature forest storing substantial quantities of carbon, with minimal effects from nearby construction. However, it is possible that the mangrove forest estimate is an underestimate due to being in recovery, and most carbon being stored in soil and dead roots. These results only partially support the hypothesis and indicate surprising tropical forest carbon storage efficiency overall.

ACKNOWLEDGEMENTS

This project would not have been possible without the help and support of several individuals. Firstly, many thanks to my project advisor, Dr. Eric Manzane, for helping me refine my project topic and proposal. Additionally, I would like to thank Academic Director Aly Dagang for helping me select a research site and providing endless support, as well as the SIT Panama program for providing me with research materials. Special thanks to the Serracin Family, namely Sra. Juany, for granting me access to Drago Dos and Fidencia Forest and providing me with a history and background of the area. I would also like to thank Ormelio Dixon for introducing me to these forests as a guide and taking me to the mangrove forest on several occasions. Thank you to Sr. Eligio for sharpening my machete, without which forest travel would have been extremely difficult. Special thanks to the researchers of the 2021 Paniagua-Ramirez et al. Study, namely Alexandra Paniagua-Ramirez and William Cooper, for working with me directly to use and understand their allometric equation. I would like to also thank my fellow SIT students for providing me with mangrove forest tree data. Specifically, thank you to Allison Collins and Drew Stein, for accompanying me into the forests for safety. Lastly, thanks to Gabriel Jacome, who taught me about mangrove forest ecosystems and provided background information about the mangrove forest used in this study. Without the support of all these individuals, this project would not have been possible.

TABLE OF CONTENTS

INTRODUCTION

Background and Research Interest

Today, trees are considered highly effective natural carbon sinks, greatly reducing the overall negative effects of anthropogenic carbon emissions. However, their exact contributions as carbon sinks, especially in tropical areas, have not been fully assessed. This study examined the carbon storage capabilities of tropical trees in the Bocas Del Toro region of Panama. Specifically, carbon storage in trees was estimated at a private forest called Drago Dos, near Boca Del Drago on Colón Island. As an extension, tropical forest carbon storage was compared to mangrove tree carbon storage within the Boca Del Drago mangrove forest, based on new and previously taken measurements. The Bocas Del Toro province is located on the Caribbean side of western Panama, near the Costa Rican border. This area houses a wide variety of marine and terrestrial biota. The mainland is composed of mountainous and lowland humid tropical forests, peat-swamps, and banana plantations. The Bocas Del Toro region has above-average precipitation as well as generally high temperatures and sun exposure. Mangrove forests in Bocas Del Toro cover a span of roughly 28 km^2 and are uniquely productive ecosystems. Deforestation has been recorded on some of the larger islands in Bocas Del Toro and generally there is a high level of tourism (Collin 2005).

The Bocas Del Toro region is particularly susceptible to climate change and anthropogenic impacts, namely from sea level rise, deforestation, and tourism (Grajales-Saavedra et al. 2021). Colón Island is one of 6 major islands in the region, and one of the only islands in which old-growth forests still remain. It also includes several mangrove forest systems. The presence of old-growth forests makes this island a prime subject for carbon storage assessment, as trees have been able to store carbon for decades with minimal disturbance relative to the other islands. Overall, the island is composed of tropical old-growth forests, secondary forests, mangrove swamps, beaches, and coral reef systems (Collin 2005).

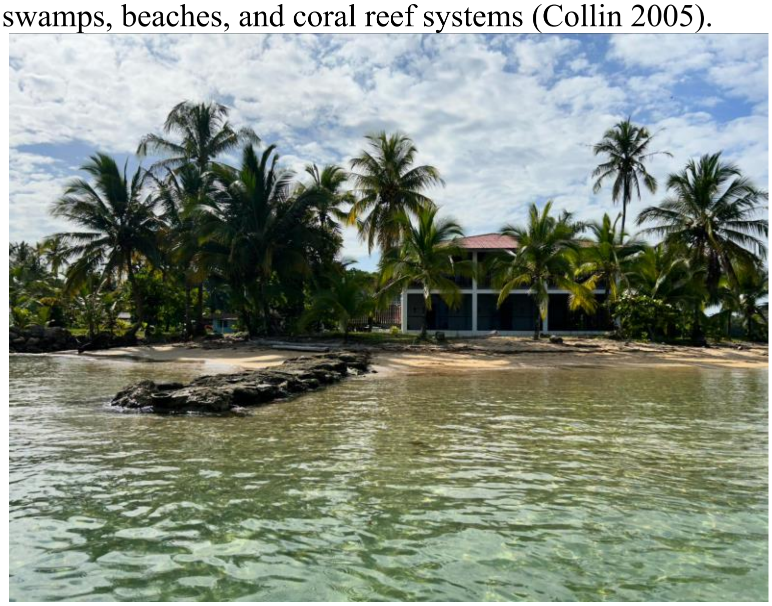


Figure 1. Main port at Boca Del Drago.

Study Site Background & History: Drago Dos

This study took place on land owned by the Serracin Family, who have lived on Colón Island for decades. The Serracin Family owns about 105 hectares of land in total, divided between 2 forests: Drago Dos and Fidencia (J. Serracin, personal communication, April 4, 2023). This land was purchased from the Dixon Family almost 70 years ago (O. Dixon, personal communication, April 4, 2023). The forests are located on both sides of the main road from Boca Del Drago to Bocas Town, starting at the crossroad between Boca Del Drago and Mimbi Timbi. Drago Dos, the forest in which this study took place, is the larger of the two, spanning approximately 80 hectares in area. It has been largely undisturbed since and prior to its purchase, making it considered an old-growth forest. As a result, it protects a wide variety of tree species, large trees, and dense vegetation and wildlife. Fidencia, only covering about 25 hectares, is considered a secondary forest. Prior to its purchase, the land was used for banana plantations and farming (O. Dixon, personal communication, April 10, 2023). Some large gaps are still visible in this forest because of past clearcutting. Neither forest has been previously assessed for carbon storage, making them ideal subjects for this type of research.

Figure 2. Entrance to Drago Dos Forest.

Study Site Background & History: Mangrove Forest

This study also involved research in a nearby mangrove forest. Specifically, a mangrove swamp southeast of Boca Del Drago was chosen for research due to its proximity and dense tree coverage. Until roughly 1994, this forest was clear cut for charcoal production and is now in the process of full-scale recovery, making it a secondary forest (A. Dagang, G. Jacome, personal communication, February 28, 2023). This section of the mangrove forest was small, only spanning 3-4 hectares in area. This mangrove forest grew on either side of a brackish water river, extending into the island. Generally, mangrove forests are valuable ecosystems known to protect a wide variety of wildlife while sequestering relatively high quantities of carbon (Alongi 2014).

Figure 3. The mangrove forest, growing alongside the river.

Research Aims & Overview

This study aimed to determine the effectiveness of tropical trees in Boca Del Drago as carbon sinks and compare tropical tree carbon storage to mangrove carbon storage. Carbon storage assessment in natural systems is greatly valuable information for evaluating the Climate Change Crisis and combating it. This data is generally lacking in tropical areas like Boca Del Drago (Martin et al. 2011). This experiment took tree size measurements, specifically tree height and DBH, using allometric equations to estimate overall carbon storage. It was hypothesized that carbon storage would be greater than average in Drago Dos, due to high light exposure, humidity, and minimal disturbance. Additionally, it was hypothesized that carbon storage would be even more efficient in the mangrove forest due to the renowned efficiency of these systems as carbon sinks (G. Jacome, personal communication, February 25, 2023, Alongi 2014). Overall, this study aimed to provide valuable information about the roles of tropical trees as natural carbon sinks, to combat the increasingly urgent effects of climate change.

LITERATURE REVIEW

The Climate Change Crisis

Climate change is one of the most urgent threats against humanity today and is exacerbated by anthropogenic carbon emissions. Carbon dioxide is currently considered the primary greenhouse gas, constituting roughly 81% of total greenhouse gas emissions. For decades, scientists have begun to explore the capabilities of plants removing atmospheric CO_2 via photosynthesis. The current effectiveness of plant carbon storage has not been wholly evaluated (Paniagua-Ramirez et al. 2021). Atmospheric carbon dioxide concentrations are constantly increasing due to human activities, causing global temperatures to rise at unprecedented rates and a myriad of other negative, environmental effects. Some of these effects are already believed to be irreversible and atmospheric temperature increases due to rising CO_2 concentrations may not decrease significantly even if CO_2 emissions were halted (Solomon et al. 2009).

Natural Carbon Sinks

Therefore, while most current research has focused on decreasing outgoing emissions, systems that capture emitted atmospheric CO_2 are also incredibly valuable. While synthetic carbon capture is an alternative that is gaining popularity, most carbon today is stored in natural carbon sinks. Of natural carbon sinks, trees store vast amounts of atmospheric carbon dioxide. Specifically, trees comprise about 30% of global land area and store about 60% of terrestrial carbon (Whitehead 2011). The importance of forests in the context of carbon storage and combating climate change has become increasingly relevant. Optimistically, planting forests can be considered reverse engineering human-caused deforestation by providing more natural carbon reservoirs (Paniagua-Ramirez et al. 2021).

Within global tree populations, tropical forest systems are remarkably efficient carbon sinks. Worldwide, tropical forests store up to 50% of terrestrial carbon while only covering 7-10% of surface land area (Martin et al. 2011). It is estimated that there are 1.8 billion hectares of tropical forest worldwide, comprising around 45% of forest land. These tropical forests have the highest potential for carbon storage as tropical species have the highest carbon densities among all forest types (Paniagua-Ramirez et al. 2021). Efforts to optimize tree-sequestered carbon in non-tropical areas, for example in US national parks, are also receiving more focus, but generally these areas store carbon significantly less effectively than in tropical forests (Banasiak et al. 2015). In the process of climate change mitigation, emissions that cannot be reduced can be offset by managing and preserving forest systems more effectively (Paniagua-Ramirez et al. 2021).

Tropical Forest Carbon Storage Estimation

Estimates of carbon storage in tropical forests are beginning to occur more regularly and generally reveal vast amounts of carbon being stored in relatively small natural areas. This estimation can be hugely important toward enhancing and protecting ecosystem productivity as well as combating climate change (Yin et al. 2012). Generally, carbon storage in tropical trees is estimated by recording tree size and volume measurements (typically height and DBH) and using allometric equations to convert to biomass and stored carbon values. For example, this methodology was successfully used to compare carbon sequestration between tree species in an urban forest in Uttar Pradesh, India (Behera et al. 2022). These studies demonstrate the importance and successfulness of tropical tree carbon storage estimation, using relatively straightforward procedures. They also highlight the need for more research and improvement in this field (Behera et al. 2022, Paniagua-Ramirez et al. 2021). Tree DBH is usually measured manually using devices like diameter tape, which convert the circumference of a tree to its diameter upon being wrapped around it. Height can be measured using measuring sticks, range finders, or other such methods (Paniagua-Ramirez et al. 2021).

Estimates of tree carbon storage can also be more comprehensive, considering a variety of tree growth factors to attain an accurate estimate of carbon capture. One such study was carried out to estimate carbon storage in a tropical forest in Monteverde, Costa Rica. A typical mature forest in Costa Rica, with a climate very similar to western Panama, stores roughly 447 tons of CO_2 per hectare. In this study, random plots were selected within two different forests at the CIEE Sustainability center, taking DBH and height measurements while recording tree species. In total, 60 different tree species were observed between the two forests. While identifying tree species accurately requires expert knowledge, certain allometric equations use species type to more accurately account for carbon storage differentiating between trees. For example, this study developed an equation that combined DBH and tree height with a variety of other factors related to tree species and development. This included fitting factors, how trees vary in diameter with height at different rates, basic specific weight, relating to wood density, and other such factors. This equation was used for this project, with assistance from these researchers, and this is explained later in further detail (See "Methods"). In the Costa Rica Study, it was estimated that the forests stored over 18,000 tons of CO_2 in total. (Paniagua-Ramirez et al. 2021).

Mangrove Forest Carbon Storage

There are many different subtypes of tropical tree systems, and among the most ecologically efficient are mangrove forests. This is because these trees have larger amounts of carbon stored below-ground compared to typical terrestrial trees and it is also stored in mangrove soil and dead roots. Generally, they are regarded as highly efficient carbon sinks and their removal would result in significant, harmful gas emissions. Mangrove forest systems typically store proportionally more carbon below-ground compared to terrestrial forest systems. Additionally, most mangrove carbon is stored as large pools in soil and dead roots rather than in the trees themselves (Alongi 2014).

Carbon and biomass measurements within mangrove forests traditionally follow the same general techniques as for tropical forests, taking tree size measurements in designated plots and converting these values into biomass and carbon with allometric equations. Though, other measurement systems are being researched, including using UAV-based imagery (Jones et al. 2020). Traditional methodology was employed to measure mangrove forest carbon storage at Paliat Island in East Java. Allometric equations were used to estimate carbon stock at around 10.80 ton/ha (Hidayah et al. 2019).

Gaps for Further Research

Extensive carbon storage estimation in tropical forest systems would provide important ecological information and is generally lacking. Carbon estimation has been determined in tropical countries like Panama to need methodological improvements and more data. Carbon storage estimation in these areas can continue to provide valuable ecological data with greater focus (Martin et al. 2011). The potential of optimizing natural systems to store carbon emissions is becoming increasingly recognized and relies on accurate estimates of current natural carbon storage. Many experiments are being conducted, especially in tropical areas, to provide this data and it will become increasingly important to reduce atmospheric carbon emissions and the potentially devastating effects of climate change (Paniagua-Ramirez et al. 2021).

RESEARCH QUESTION

What is the average carbon storage (tons/ha) of trees in Drago Dos Tropical Forest in Boca Del Drago, Panama? By extension, how does this compare to the average carbon storage of trees in a nearby mangrove forest?

METHODS

Drago Dos Data Collection

Measurements for tropical tree carbon storage estimation were taken at Drago Dos Forest, a mature, ~80-hectare tropical forest growing along the North side of the main road from

Boca Del Drago. The Drago Dos Forest entrance is located at (9.417141, -82.31867), shown in Figure 4. An estimation of the expanse of Drago Dos Forest is also shown in Figure 4, highlighted in yellow. For the purposes of this study, a subsection of this forest was defined as the testing region because the entire forest was too large to travel through given the time constraints. The exact coordinates of the corners of this testing region are as follows: (9.4195004, -82.3157536), (9.4204573, -82.3185657), (9.4183131, -82.318825), and (9.4308492, -82.317415). A visual of the location of Drago Dos relative to Colón Island is shown in Figure 5.

Twenty 5x5 m square subplots were defined within the testing region, totaling 500 m^2 (Paniagua-Ramirez et al. 2021). These plots were selected using a random number generator to generate coordinates within the defined box and rerolling if a given coordinate overlapped with a previously defined plot. Plots were measured out with measuring tape and marked using marking tape. The distribution of these plots within the defined testing region is shown in Figure 4. Within each plot, size measurements were taken for all upright trees. Trees shorter than 2 meters were excluded from measurement (Behera et al. 2022). For each qualifying tree, DBH (in cm) was recorded using diameter tape at a constant height of 1.3 m from the ground, as shown in Figure 6 (Paniagua-Ramirez et al. 2021). Then, the height of each tree (in m) was measured using a range finder, as shown in Figure 7. Height and DBH are the most typical size measurements collected to estimate carbon storage in tropical trees (Behera et al. 2022, Paniagua-Ramirez et al. 2021, Hidayah et al. 2019). Tree species were not identified as no expert was present to do so accurately.

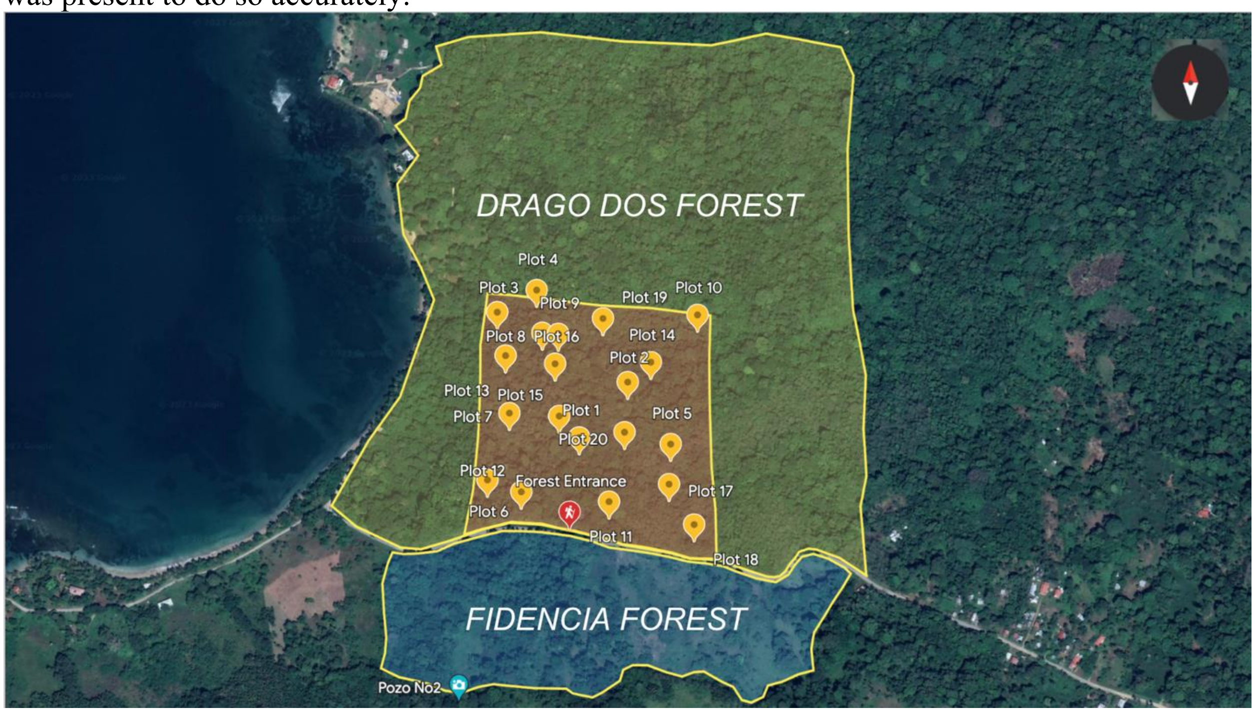


Figure 4. Satellite map visual estimation of forest and testing region boundaries, based on GPS coordinates taken during study. Drago Dos (highlighted in yellow), the testing region (highlighted in red), and Fidencia (highlighted in blue) are shown. Aerial view shows Drago Dos is noticeably denser than Fidencia, consistent with the fact that it is an old growth forest.

Figure 5. Closeup view of subplot distribution (left) and Drago Dos location, relative to the entire island (right).

<u>Drago Dos Carbon Storage Estimation</u>

After tree size measurements were taken for all qualifying trees within the defined subplots in Drago Dos, an allometric equation developed by Paniagua-Ramirez et al. was used to estimate carbon storage within the measured trees. This equation was developed for tropical trees in Costa Rican forests, in an area with similar climatic and forest conditions as Drago Dos (Paniagua-Ramirez et al. 2021). This equation is shown below:

$$CO_2e = DBH^2 * (\pi/4) * h * FF * CF * BSW * BEF_a * BEF_g * 3.67$$

This equation estimates CO_2e, or the total amount of CO_2 captured by each tree. $DBH^2 * (\pi/4)$ is the basal area, whereas *h* represents the height of a given tree. The remaining variables are fitting factors accounting for IPCC guidelines, as trees are not perfectly cylindrical. FF, or the Form Fitting factor, accounts for changing tree diameter with height. A value of 0.7 was used for all trees in this experiment as specific tree species could not be identified and this value is permissible within IPCC guidelines. CF, or the carbon fraction, estimates the amount of carbon stored in the trunk, which is typically ~50% of the biomass of a tree. Because of this, a value of 0.5 was used for all trees in this experiment. Next, BSW, or the basic specific weight, represents the weight of dry wood in each tree. A value of 0.5 was used for all trees in this experiment as specific tree species could not be identified and this value is permissible within IPCC guidelines. The variables BEF_a and BEF_g represent the volume of leaves and branches, and roots respectively. For both, this is estimated as 1.2 times the volume of the tree trunk, calculated as basal area multiplied by tree height. Finally, 3.67 is a conversion factor from carbon to CO_2 based on atomic weight (Paniagua-Ramirez et al. 2021). DBH and height measurements for each tree were plugged into this equation and the results were summed and converted to tons/ha.

Figure 6. DBH measurement using diameter tape in Drago Dos.

Figure 7. Tree height estimation using range finder in Drago Dos.

Mangrove Forest Data Collection

Measurements for mangrove tree carbon storage were taken in a nearby mangrove forest southeast of Boca Del Drago. This forest bordered an inland river, as shown in Figure 8, and all measurements were taken on its southern shore. The testing region had exact coordinates of (9.401603, -82.3086519), (9.4007787, -82.3103998), (9.4005015, -82.3093117), and (9.4010836, -82.3082365). Because of time constraints, mangrove tree size data previously collected by SIT students (taken between Feb. 26, 2023 - Feb. 28, 2023) was used for this study. This data came from 5 radial sampling plots with 5 m radii, evenly dispersed within the testing region. Four 5x5 m square plots were additionally established within this testing region. This was done using a random number generator to generate coordinates within the defined box and rerolling if it overlapped with a previously defined plot. Plots were measured out with measuring tape and marked using marking tape. The distribution of these plots within the testing region is shown in Figure 8. These new plots were taken to ensure that the total testing land coverage was similar in size to that of Drago Dos. Between the radial sample plots and the new square plots, 493 m^2 of mangrove trees were sampled.

Within each plot, all upright trees taller than 2 m were measured for DBH and tree height. DBH was measured at a height of 1.3 m from the ground, using diameter tape, as shown in Figure 9 (Hidayah et al. 2019). Tree height was measured using an extendable measuring stick and range finder, as shown in Figure 10 (Jones et al. 2020). Since the measuring stick only extended up to 16 feet, the range finder was used to measure trees taller than this. Because the previous measurements capped tree height at 16 feet, the range finder was used at random points throughout the mangrove forest to roughly determine the average height. This average height was then plugged into the previously collected data, to represent actual tree height more accurately, avoiding an underestimate of stored CO_2. The actual average mangrove tree height was determined to be 6.43 m, or 21.1 feet.

Figure 8. Satellite map visual estimation of mangrove forest and testing region boundaries, based on GPS coordinates taken during study. The testing region (highlighted in yellow) and main river (highlighted in blue) are shown. The boundaries of the mangrove forest are clearly seen, as the mangrove trees are considerably denser and a lusher green.

Figure 9. DBH measurement using diameter tape in mangrove forest.

Figure 10. Tree height estimation using extendable measuring stick (left) and range finder (right) in mangrove forest.

<u>Mangrove Forest Carbon Storage Estimation</u>

After tree size measurements were taken for all qualifying trees within the defined subplots in the mangrove forest, an allometric equation developed by Komiyama et al. was used to estimate the carbon stored by each tree. This equation was developed specifically for tropical mangrove trees and is shown below:

$$W_{top} = 0.178 * DBH^{2.47}$$
$$W_R = 0.00974 (DBH^2 * h)^{1.05}$$

These equations estimate above-ground carbon storage, W_{top}, and below-ground carbon storage, W_R (Komiyama et al. 2008). This distinction is especially necessary with mangrove trees as they store disproportionately more carbon below ground than terrestrial trees (Alongi 2014). In these equations, DBH represents the diameter at breast height of each tree and *h* represents the tree height. Above and below-ground carbon estimates were summed for each tree to calculate total CO_2 storage per tree (Komiyama et al. 2008). These were then summed and converted to tons/ha of stored CO_2, so the results could be compared to those of Drago Dos.

<u>Methods of Data Analysis</u>

After tree size measurements were converted to carbon storage estimates, these results and initial size measurements were analyzed in various ways. Firstly, two-tailed t-tests were run to compare the DBH and height between sites. Two-tailed t-tests were also conducted to compare carbon storage between the two forests. Summary statistics were obtained on size measurements at each site and linear regression analysis was performed to identify any correlations between DBH and height at each site.

ETHICS

There were not many substantial ethical concerns involved with this study. The most significant ethical concern was habitat disruption. This project involved entering a private, tropical forest and could have accidentally led to minor environmental damage. Tree saplings and plants could have been trampled, and wildlife could have been disturbed while taking measurements. To minimize these impacts, special care was taken while traveling through the forest and taking measurements to not harm any wildlife and minimally change natural habitats. The Serracin Family also requested that no plants or animals be removed from the forest. While traveling through the forest, machetes were used minimally and only as necessary to reduce habitat damage. A variety of wildlife was observed, including frogs, birds, monkeys, insects, lizards, and more. While walking, each step was taken with care to avoid stepping on any of these organisms and all traces of the experiment were cleaned up prior to leaving the forest. Prior to experimentation, an Institutional Review Board (IRB) Form was submitted to SIT, outlining the details of the project to ensure no community or habitat was being put at risk. Since there were no human subjects involved in this study, the short version of the form was completed and approved after ethical consideration.

Figure 11. Special care was taken to avoid stepping on small creatures, like this frog found in Drago Dos.

RESULTS

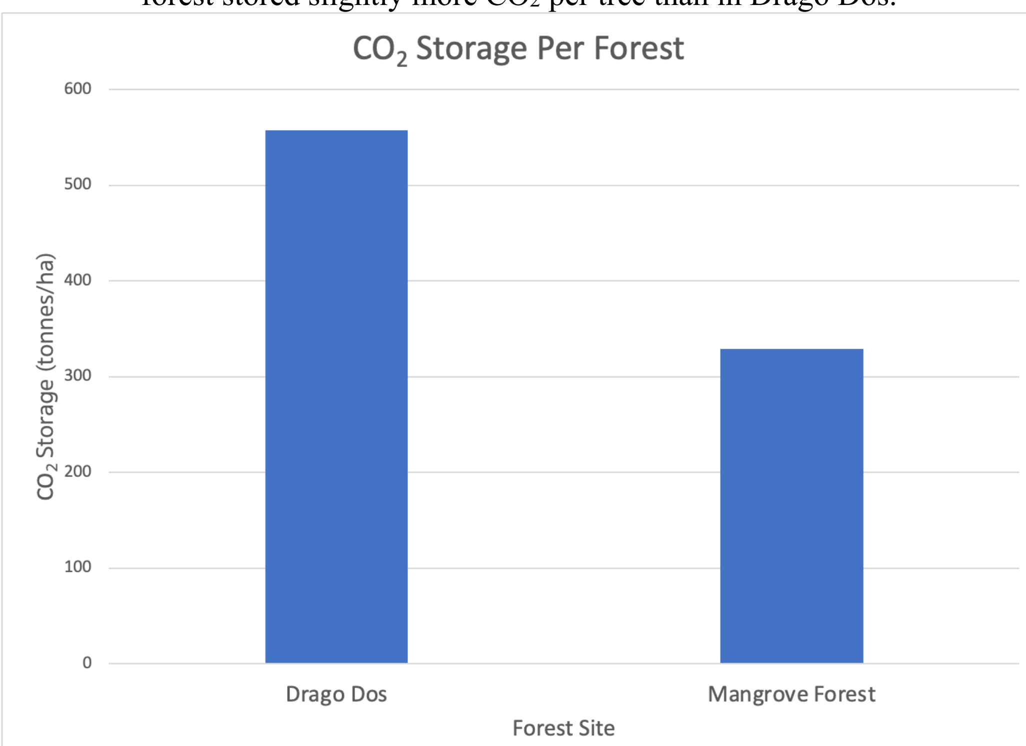
Graphs and Tables

Variable	Drago Dos	Mangrove Forest	Typical Mature Forest (National Forest Inventory of Costa Rica)
CO_2 (tons ha^{-1})	557	329	447
Number of Trees (ha^{-1})	7380	4000	N/A

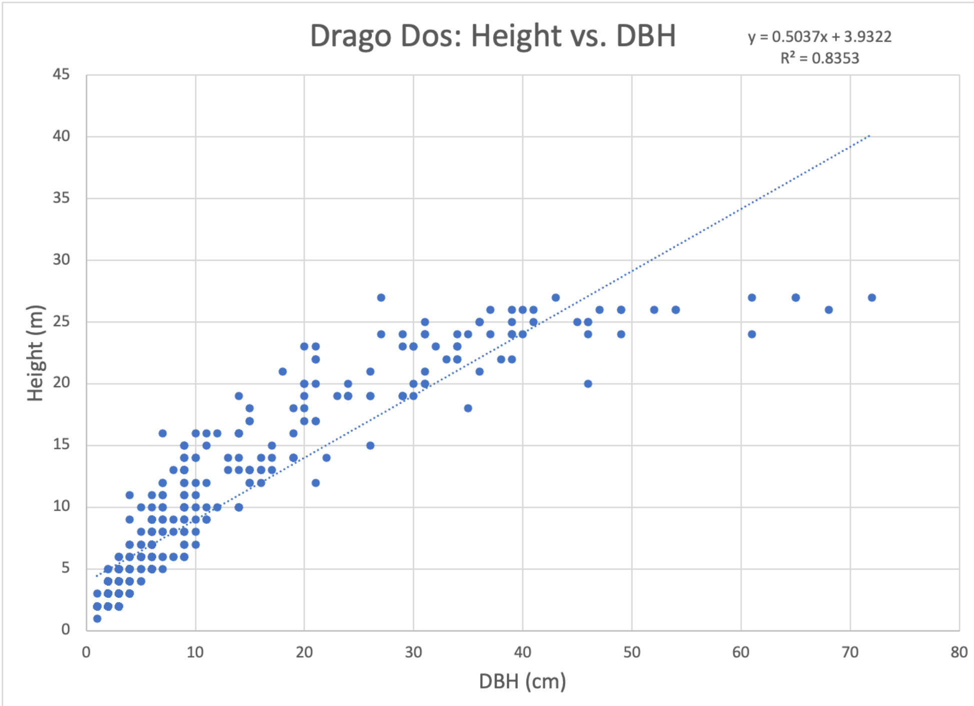
Table 1. Carbon Storage and Tree Density in both forests, compared to a typical mature tropical forest in a similar climate (Paniagua-Ramirez et al. 2021). Carbon storage was greater in Drago Dos than typical carbon storage in similar tropical forests.

Variable	Drago Dos	Mangrove Forest
Tree Count	369	200
Average DBH (cm)	12.52	7.79
Average Height (m)	10.24	6.43
Average CO_2 per tree (kg)	75.55	82.18
Maximum DBH (cm)	72.1	64.4
Minimum DBH (cm)	1.0	2.0
Maximum Height (m)	27	4.92
Minimum Height (m)	2	7.50
Maximum CO_2 stored/tree (kg)	641.26	3749.61
Minimum CO_2 stored/tree (kg)	0.33	1.22

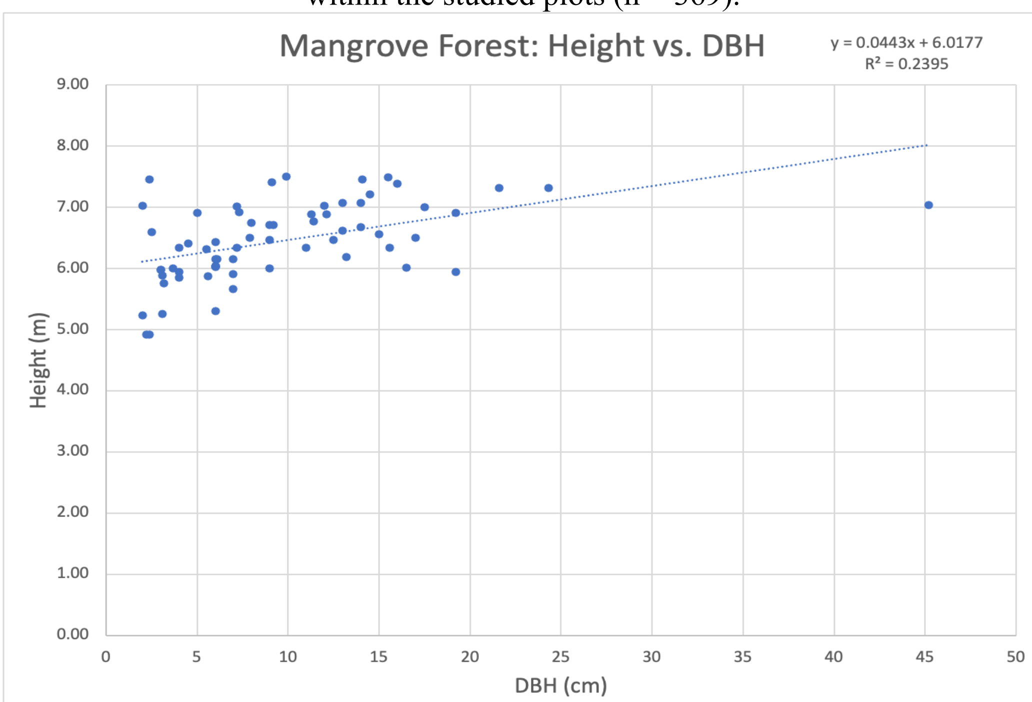
Table 2. Summary Statistics of both forests. Trees were determined to be significantly taller in Drago Dos than in the mangrove forest ($p = 9.23E-19$). Trees were determined to be significantly larger in DBH in Drago Dos than in the mangrove forest D. However, trees in the mangrove forest stored slightly more CO_2 per tree than in Drago Dos.



Graph 1. CO_2 storage (tons/ha) at each site. While noticeably more CO_2 is stored per hectare at Drago Dos, this is not a significant difference ($p = 0.39$).



Graph 2. Linear Regression analysis of Height vs. DBH in Drago Dos. There is a somewhat linear positive relationship between these factors (R^2 = 0.84). This is based on data from all trees within the studied plots (n = 369).



Graph 3. Linear Regression Analysis of Height vs. DBH in mangrove forest trees. This relationship has a slightly linear positive correlation (R^2 = 0.24). This analysis was performed on a subset of trees with heights that were not initially capped at 16 ft. and replaced with the average height (n = 66). Using the total number of trees with this imposed average or capped values would falsely flatten this correlation (n = 200).

Results Summary

These results indicate that almost twice as much CO_2 was stored per hectare in Drago Dos than the mangrove forest. However, on a per tree basis this difference is not statistically significant. Drago Dos also had a higher tree density than the mangrove forest. 369 trees were surveyed in Drago Dos whereas only 200 were measured in the mangrove forest. CO_2 storage per hectare was also found to be higher in Drago Dos than in a typical mature forest in Costa Rica, nearby to the project site (Paniagua-Ramirez et al. 2021). Trees in Drago Dos Forest were significantly larger, in both height and DBH, than mangrove trees. Trees stored slightly more carbon per tree in the mangrove forest than in Drago Dos. There was a somewhat linear positive correlation between height and DBH in Drago Dos whereas in the mangrove forest there was a slightly positive correlation between them.

DISCUSSION

Drago Dos Carbon Storage

The results of this project provided interesting and somewhat surprising answers to the initial research question. Firstly, the average CO_2 storage of trees in Drago Dos Forest, as seen in Table 1, was successfully found to be 557 tons/ha. This result is very similar to the carbon storage totals found in the Zapote Forest in the Paniagua-Ramirez et al. study. This forest was the more mature forest of the two they sampled and was found to store 518 tons/ha of CO_2 (Paniagua-Ramirez et al. 2021). This is a promising result that experimental findings were on a similar magnitude to previous research within a similar forest, indicating accuracy. While the Zapote Forest is not in Panama, Costa Rica is an adjacent country with largely similar weather conditions, making it a reasonable comparison for this study. Such data in these convenient units is not as readily available from Panamanian forests (Martin et al. 2011).

However, the National Forest Inventory of Costa Rica provided comprehensive data about typical CO_2 storage of various forest types in the region. According to this inventory, the typical mature forest in Costa Rica stores 447 tons/ha CO_2 (Paniagua-Ramirez et al. 2021). Interestingly, Drago Dos was found to store CO_2 more efficiently than this, by 110 tons/ha. This is consistent with the fact that Drago Dos is a mature forest with minimal past disturbance to reduce carbon storage efficiency. It also indicates a surprisingly efficient level of carbon storage for an area with such high levels of tourism, but speaks to the effectiveness of tropical ecosystems, proper forest management, and natural carbon sinks. In total, based on its per hectare carbon estimate, Drago Dos stores roughly 44,560 tons of CO_2 today. This substantial quantity of carbon storage was able to accumulate likely due to decades of being unused for commercial practices and being protected by the Serracin and Dixon families (O. Dixon, personal communication, April 10, 2023). This also suggests that protected areas effectively guard valuable ecosystem services, potentially combating anthropogenic effects.

Drago Dos is also adjacent to various tourist sites and is being pressured by current construction efforts to expand and repave the main road. Even in the face of such adversity, it sequesters an above-average quantity of CO_2, speaking to the resiliency of natural carbon sinks. It is unclear how these activities may affect forest growth and health in the future, but the results of this experiment indicate that it is a resource worth protecting. As seen in Table 2, Drago Dos has a remarkably high tree density, and high average tree height and DBH values, indicating general forest health. Drago Dos has been protected by the Serracin Family for decades despite commercial motivations (J. Serracin, personal communication, April 4, 2023). Perhaps systems such as Payment for Environmental Services (PES) would effectively provide a substantial incentive to protect natural carbon sink assets for decades to come (Börner et al. 2017). Based on this study and previous research, tropical forests are highly effective natural carbon sinks that should be protected and more fully evaluated in the future (Behera et al. 2022, Paniagua-Ramirez et al. 2021, Hidayah et al. 2019).

Comparison to Mangrove Carbon Storage

Perhaps most surprisingly, the results of this experiment indicated that mangrove trees stored CO_2 less efficiently (fewer tons/ha) than trees in Drago Dos. Previous research has suggested mangrove forests to be among the most efficient natural carbon sinks today (Alongi 2014, Hidayah et al. 2019, Jones et al. 2020). However, as seen in Graph 1, this study found that CO_2 was stored in the mangrove forest with an efficiency of 329 tons/ha, compared to 557 tons/ha CO_2 stored in Drago Dos. While this difference is not statistically significant overall ($p = 0.39$), it was initially surprising that the mangrove forest stored carbon with lower efficiency.

However, there are a variety of possible explanations for this surprising result. Firstly, it is worth noting that while CO_2 storage was greater on a per hectare basis in Drago Dos, CO_2 storage was slightly greater per tree in the mangrove forest. Specifically, as seen in Table 2, trees stored 75.55 kg CO_2 on average in Drago Dos and 82.18 kg CO_2 on average in the mangrove forest. Overall differences in carbon storage between the forests was therefore mainly limited by differences in tree density. As seen in Table 1, there were 7,380 trees/ha in Drago Dos versus just 4,000 trees/ha in the mangrove forest. It is possible that tree density in the mangrove forest was especially lacking because the forest is currently in succession, recovering from clearcutting for charcoal production until 1994 (A. Dagang, G. Jacome, personal communication, February 28, 2023). While Drago Dos has been protected from commercial activities for many decades, the mangrove forest is still in the process of regrowth, and it is likely that its tree density will vastly increase in the future. Therefore, it may be worthwhile to repeat carbon storage measurements after another decade, to see if carbon storage efficiency has increased with regrowth.

Another possible reason why mangrove CO_2 storage was lower than expected compared to Drago Dos pertains to the methods of carbon storage estimation used. Each allometric equation used for this study calculated total biomass only in the trees of each forest system (Komiyama et al. 2008, Paniagua-Ramirez et al. 2021). However, mangrove forest systems are known to store most of their carbon in soil and dead roots rather than in upstanding trees, especially compared to terrestrial forest systems (Alongi 2014). It is possible that this experiment was looking at carbon storage in the wrong place, and that total carbon storage evaluation (assessing plant biomass as well as soil carbon storage) would reveal the mangrove forest system to store CO_2 in greater quantities per hectare than in Drago Dos. Ideally, the results of this experiment could be combined with those of a forest soil carbon assessment, to evaluate total carbon sequestration in each system.

Lastly, while mangrove trees were expectedly significantly smaller than Drago Dos tropical trees in both DBH and height ($p = 5.91E-08$ and $p = 9.23E-19$ respectively), they still stored more CO_2 per tree. This is a testament to the potential efficiency of mangrove forest systems at storing carbon and mitigating the effects of climate change. While these systems are far less expansive in area than typical terrestrial forests, they have remarkable ecological efficiency. In combination with other environmental benefits like protecting shorelines from flooding and housing countless varieties of organisms, they were found to store CO_2 with a relatively high efficiency with vast potential for future carbon storage (Alongi 2014).

Other Results & Discussion

As other studies have attempted to establish or evaluate a correlation between tree height and DBH, this study also examined the relationship between height and DBH of trees measured at both forests (Mugasha et al. 2013). The results of linear regression analysis on tree samples from each forest are shown in Graphs 2 and 3. Trees at Drago Dos were found to have a somewhat linear positive correlation between height and DBH whereas in the mangrove forest the relationship was less linear ($R^2 = 0.84$ and $R^2 = 0.24$ respectively). This is possibly due to trees in Drago Dos having a lesser range of growth stages, due to it being a mature, established forest. The trees in the mangrove forest, however, were in various stages of regrowth, possibly causing more discrepancies in the relationship between height and DBH. Additionally, this data for each forest could be fitted with non-linear curves for possibly stronger correlations.

Overall, the results of this study were logically consistent with most previous related research and suggest that tropical forest systems should be further evaluated for carbon storage.

Errors & Limitations

There were several potential sources of error and limitations during this study. Perhaps most significantly, the allometric equation used for tropical tree carbon storage estimation would have given vastly more precise and accurate values if exact tree species were known. Different tree species have varying wood densities, form fitting factors, and other qualities that could have been used to generate different carbon storage estimates. If this experiment were to be conducted again, ideally a researcher with tree identification expertise would be present to accurately identify the variety of species measured. Additionally, while the researchers who developed this allometric equation were consulted, it is possible that intricacies involved in the use of this complex equation were accidentally misused or excluded (Paniagua-Ramirez et al. 2021). Ideally, an expert level of understanding of tree allometry would provide a higher degree of reliability for tree carbon storage estimates.

Other possible sources of error in this experiment pertain to the measurement process. Firstly, in the mangrove swamp, ideally all height data measurements would be the true heights of each tree. Because initial height measurements were capped at 16 feet and replaced with a more representative average tree height, the resulting carbon storage estimates were not entirely representative of actual tree sizes. For future study, the method of height measurement should be consistent for all mangrove trees and measure full tree height, most easily using a range finder. Additionally, there could have been measurement error in range finder height calculations in Drago Dos. There is potential for human error in using the device and properly pointing it toward the base and top of the correct tree. Height values were possibly not completely accurate because of improperly reading height values on the range finder. This is also possible for DBH measurements. Certain tree species, like Panama trees, are disproportionately wide at the base, potentially causing DBH measurements to be overestimates. Also, DBH measurements could have been slightly misread or taken at slightly different heights off the ground, although this was attempted to be controlled. Lastly, if more time was allotted for this experiment to be conducted, carbon storage estimate reliability would be increased if a greater sample size of each forest was measured as typical carbon storage studies involve larger plots and study areas (Behera et al. 2022, Paniagua-Ramirez et al. 2021, Hidayah et al. 2019).

CONCLUSION

Carbon Storage Estimations

Overall, the objectives of this study were largely achieved as CO_2 storage estimates were successfully generated and compared for the Drago Dos Forest and mangrove forest at Boca Del Drago. Tree size measurements were taken in both forests and CO_2 storage was estimated using two different allometric equations (Komiyama et al. 2008, Paniagua-Ramirez et al. 2021). It was originally hypothesized that Drago Dos Forest would be found to store above average quantities of carbon per hectare compared to a typical mature tropical forest. The results of this study support this hypothesis, as Drago Dos stored 557 tons/ha CO_2 compared to a typical mature forest CO_2 storage rate of 447 tons/ha CO_2, based on the National Forest Inventory of Costa Rica (Paniagua-Ramirez et al. 2021). Drago Dos tree size measurements are consistent with a healthy, mature tropical forest, and the forest was found to store substantial amounts of total carbon despite nearby tourism and construction. Secondly, it was hypothesized that the mangrove forest would store CO_2 more effectively than Drago Dos, but experimental results reject this hypothesis. While Drago Dos stored CO_2 at a rate of 557 tons/ha, the mangrove forest had a storage rate of 329 tons/ha. However, this difference is not significant and could be due to past disturbances and mangroves storing carbon largely in soil or dead roots. Mangrove trees still showed a substantial level of carbon storage efficiency, storing more carbon per tree than Drago Dos.

The results of this experiment provide substantive evidence to reach these conclusions. In total, nearly 1,000 m^2 of land was surveyed and 569 trees were measured between the 2 forests. Random sampling was ensured to reduce bias and increase sampling reliability and experimental repetition was ensured to reduce error. The allometric equations used in this study have been tested with a high degree of reliability ($R^2 = 0.98$ for the Komiyama Equation) and clear trends and results were seen (Komiyama et al. 2008, Paniagua-Ramirez et al. 2021).

Future Steps

Based on the results of this study, several future steps could be taken to build upon this line of research. In the context of this study, it would be beneficial to revisit these forests in approximately a decade to verify if a fully restored mangrove swamp stores carbon more efficiently and to see the long-term effects of tourism and construction practices on natural carbon sinks. This study was hindered by the lack of available carbon storage data from tropical areas. In a broader context, to accurately gauge the effectiveness of global carbon sinks and combat climate change, further such experiments must be conducted in areas with little available data. Specifically, it would be ideal for Panama to conduct a National Forest Inventory, like Costa Rica, to provide a database of trends for carbon storage in various types of tropical forests.

Additionally, the results of this study demonstrate the remarkable ability of natural systems to store large amounts of CO_2, reducing anthropogenic effects of climate change. Both forests studied are protected from commercial activities today and provide priceless ecosystem services in return. Therefore, this suggests an emphasis on effective forest management and preservation, by establishing protected areas, PES, or other such methods. While the hypotheses of this study were not fully supported, valuable information with real-world applicability was collected, contributing to a broad foundation of climate change relief.

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